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PORT DOCUMENTATION PAGE

Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) MEMS-ALC-16	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 93 0138 Air Force Office of Scientific Research
6a. NAME OF PERFORMING ORGANIZATION Carnegie Mellon University	6b. OFFICE SYMBOL (If applicable)
	7a. NAME OF MONITORING ORGANIZATION Air Force Office of Scientific Research
6c. ADDRESS (City, State, and ZIP Code) Dept. of Materials Science and Engineering Carnegie Mellon University Pittsburgh, PA 15213	7b. ADDRESS (City, State, and ZIP Code) Bolling AFB, Bldg. 410 Washington, DC 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR	8b. OFFICE SYMBOL (If applicable) NC
	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR 90-0033
8c. ADDRESS (City, State, and ZIP Code) Bolling AFB, Bldg. 410 Washington, DC 20332	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 61102F; PROJECT NO. 2306; TASK NO. A5; WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Fundamentals of Mechanical Behavior in Intermetallic Compounds

12. PERSONAL AUTHOR(S)
Howe, James M. and Thompson, Anthony W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 10/1/89 TO 9/30/92	1 February 1993	14

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This research program has examined mechanical behavior and creep of titanium aluminide alloys, both based on Ti_3Al and TiAl, with the goal being better understanding of relationships between microstructure and mechanical properties of these intermetallic compound-based alloys. Detailed microstructural characterization has been conducted for both types of aluminide alloys. For Ta additions to TiAl alloys, which are thought to improve ductility, lowered stacking fault energy and increased twinning have been found. For a Ti_3Al-based alloy, detailed stress and temperature dependences of creep have been measured, and a strong microstructural dependence of creep properties has been established.

93-06617

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Howe	22b. TELEPHONE (Include Area Code) 202-767-4960
	22c. OFFICE SYMBOL NC

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

FUNDAMENTALS OF MECHANICAL BEHAVIOR IN INTERMETALLIC COMPOUNDS

FINAL REPORT
1 OCTOBER 1989 – 30 SEPTEMBER 1992

Air Force Office of Scientific Research

Grant AFOSR 90-0033
(Carnegie Mellon Account 1-52159)

J.M. Howe and A.W. Thompson
Principal Investigators

Dept. of Materials Science and Engineering
Carnegie Mellon University

Report No. MEMS-ALC-16
1 February 1993

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Fundamentals of Mechanical Behavior in Intermetallic Compounds

FINAL REPORT

ABSTRACT

This three-year program has aimed at fundamental understanding of intermetallic alloys in the Ti-Al system, particularly those based on the compounds Ti_3Al and TiAl. This work had two parts. In the first part, research was conducted on mechanical behavior and creep of a Ti_3Al alloy, Ti-24 Al-11 Nb, with an interest not only in obtaining a characterization of creep behavior but in advancing understanding of microstructural effects in creep. To that end, several different microstructures were tested to determine differences in behavior. Mechanical studies on TiAl alloys were also conducted. In the second part, work on TiAl alloys containing Ta additions examined twinning behavior, a feature which increasingly appears central to deformation processes in TiAl alloys, particularly at high strains. For the work on creep behavior of Ti-24 Al-11 Nb, the microstructural dependence of relative creep properties was explored in detail, and in concert with measurements of activation energies and stress exponents for creep, some implications for creep mechanisms in this alloy were drawn.

BACKGROUND

This is the final report on the subject program. The experimental materials forming the basis for the work are titanium aluminide intermetallic compounds, both in the α_2 or Ti_3Al family, and in the γ or TiAl family. The goal of this work was to advance fundamental understanding of the performance of alloys based on these compounds, with an emphasis on fundamentals of mechanical behavior. Although there has been extensive testing of these compounds reported in recent years, with a number of comprehensive review papers available to summarize results, it remains true that fundamental knowledge of mechanical behavior is scanty.

The first part of this program was directed to mechanical behavior as a function of microstructure, on both Ti_3Al and TiAl alloys. Much of the experimental work on creep of the Ti_3Al alloy, Ti-24 Al-11 Nb, called Ti-24-11 hereafter, was completed in the first year of this program; those results were analyzed in detail in the second year, and a number of additional experiments were made to test the conclusions drawn from analysis of original data. With the completion of all work, both experiments and analysis, on creep of Ti-24-11, the Ph.D. thesis of Diane E. Albert was defended in June, 1991. Completion of writing of journal articles on the work has taken place since that time.

The second part of the program involved work on compositional modifications to TiAl alloys and examination of the resulting microstructural changes. Much of this work explored effects of Ta and Mn additions to TiAl alloys. Such ternary additions, utilizing the classic β stabilizing elements familiar from titanium metallurgy, are already known to affect the properties of the two-phase lamellar microstructures, alternating plates of γ and α_2, which appear to offer optimum mechanical properties in TiAl alloys. Experimental work indicated that the Ta additions affected twinning behavior, with lowered stacking fault energy in the γ phase being evident. It appeared that this extrinsic faulting acted as nuclei for twins. Interfacial structure within the lamellar microstructures was also altered by Ta additions. Both these effects hold out the promise of being effective means of controlling mechanical behavior and thus optimizing mechanical properties of TiAl alloys. Further work by J.M. Howe on these topics is proceding under separate sponsorship.

The original Co-investigator, J.M. Howe, moved to the University of Virginia in January, 1991. During calendar year 1991, his portion of the program was carried out there. The second portion of this report summarizes work done by Prof. Howe both at Carnegie Mellon and at Virginia. During the period January 1–September 30, 1992, the sole Investigator was A.W. Thompson. Graduate students supported at Carnegie Mellon include S. Rozeveld, S.R. Singh, D. E. Albert and K. Li.

FINAL TECHNICAL REPORT
1 October 1989 – 30 September 1992

Part I

CREEP OF AN ALPHA-2 TITANIUM ALUMINIDE ALLOY

Anthony W. Thompson, Principal Investigator

The experimental creep measurements on Ti-24 Al-11 Nb, or Ti-24-11, described in some detail in the first year's report on this program, were extended and completed in the second year. This alloy was mong the first accepted engineering alloys of a titanium aluminide composition, and the microstructure of this material is primarily α_2 or Ti_3Al in structure. A number of microstructural effects are known to be important to mechanical behavior of the alloy in general, and creep behavior shows the same dependence. It was found that the types of microstructure effects in Ti-24-11 are dependent on the temperature of the creep process. At the highest temperatures, consonant with understanding of creep in general, the coarser scale microstructures are most resistant to creep. Refinements in our data in the second year confirmed the first-year finding, that such coarse microstructures are only effective if the coarse constituent is an individual α_2 plate, rather than part of a colony or packet of parallel α_2 plates, sharing a common orientation. This appears to be because the parallel plates can act mechanically, to some extent, like a single, larger unit with a longer slip distance, with the plate boundaries within the colony acting as rapid diffusion paths to aid any boundary sliding at the higher temperatures. Examples of these microstructural types are shown in Fig. 1.

This interpretation is confirmed by measurements of activation energies and of stress exponents, n, for creep in these tests. Only at the lowest stresses and highest temperatures was evidence found for a contribution to creep by diffusive processes, in the form of relatively low activation energies, near 120 kJ/mol, and low stress exponents, roughly of the order of $n = 2$. As temperatures were lowered from 870°C, the highest used, or as stresses were raised above 32 MPa, stress exponents rose to near a value of four, and activation energies were much larger, such as 300 kJ/mol. These latter values indicate dislocation process of creep were dominant under these conditions, such as diffusion-assisted glide and climb, and represent a different mechanism of deformation than that seen at the highest temperature and lowest

stress. Detailed consideration of the literature on creep mechanisms showed that this interpretation is consistent with all experimental observations, as we have reported in the publications listed below. Examples of the results are shown in Fig. 2.

Under the conditions of dislocation creep, the microstructure dependence of behavior was different than under the high-temperature conditions. Effects more like those observed at ambient temperature were detected, such as slip-length effects, with finer-scale microstructures more effective than coarse ones. It should be noted that this was observed at temperatures such as 650°C, which is already above the accepted use temperature for even the best of the conventional titanium alloys under creep conditions.

Final Year Results

Mechanical properties of two alloys based on TiAl or γ phase, both obtained from commercial sources, were studied in preliminary work during the third year of the program. One of these is the well-developed composition Ti-48 Al-2 Cr-2 V, or Ti-48-2-2, from General Electric Aircraft Engines, in both forged and rolled product forms. A second alloy, Ti-48 Al-2 Mn, or Ti-48-2, has been supplied by Macdonnell Douglas, and offers the opportunity for different variations in microstructure as a function of heat treatment, as well as building on the work by Howe's group in the first year of this program.

The 48-2 alloy is stronger than 48-2-2 but has less ductility and toughness, obtained from different microstructures. Both alloys develop the best combinations of strength and toughness when prepared with the microstructure containing a moderate amount of primary γ phase, with a predominant amount of lamellar γ and α_2. This lamellar constituent is remarkably uniform in its alternating plates of the two phases, and fracture appears to occur separately in individual plates, with some contribution to toughness arising from interphase interface fracture. Several observers, including ourselves, have noted that fracture facets are often not flat, but are curved or conchoidal, raising the complex question of what combination of brittle fracture mechanisms operating on the micro-scale could interact on a meso-scale to produce such facet shapes.

A further factor is deformation of the alloy by twinning. This process may

assist fracture through develoment of sharp strain gradients at grain and phase boundaries. We have conducted a series of examinations on microstructures prepared with various heat treatments to begin investigation of this problem. Observations of microcracking within the microstructural constituents is a first step in understanding this behavior, but can only address the initiation portion of the fracture event. Detailed fracture observations would be needed to examine the full fracture process, and determine the extent of the role of twinning both in nucleating and in propagating fracture in the two-phase lamellar TiAl microstructures.

AFOSR-supported publications in program period

Previous program:

1. J. Chene, I.M. Bernstein and A.W. Thompson, "Role of Heat Treatment and Cathodic Charging Conditions on the Hydrogen Embrittlement of HP 7075 Aluminum Alloy," *Metall. Trans. A*, 21A (1990) 455-464.

2. A.W. Thompson, M.P. Mueller and I.M. Bernstein, "Stress Corrosion Cracking in Equiaxed 7075 Aluminum Under Tension and Torsion Loading," *Metall. Trans. A*, submitted.

3. C.P. You, M. Dollar, A.W. Thompson and I.M. Bernstein, "Microstructure Property Relationships and Hydrogen Effects in a Particulate-reinforced Aluminum Composite," *Metall. Trans. A*, 22A (1991) 2445-2450.

4. R.F. Buck and A.W. Thompson, "Environmental Fatigue in Al-SiC Composites," in *Environmental Effects on Advanced Materials*, R.H. Jones and R.E. Ricker, eds., TMS-AIME, Warrendale, PA (1991) 297-313.

5. A.W. Thompson and R.F. Buck, "Fatigue Crack Growth Behavior of SiC-Reinforced Aluminum-Alloy Composites in Aggressive Environments," in *Composites* (Proc. 8th Int. Conf. on Composite Materials, ICCM/8), S.W. Tsai and G.S. Springer , eds., SAMPE, Covina, CA (1991) Vol. 1, 20A-1 to 20A-12.

Present program:

1. A.W. Thompson, "Creep of Alpha-2 Titanium Aluminides," in *Titanium Aluminides* (papers from Aeromat '90), C.G. Rhodes and H.A. Lipsitt, eds., Rockwell Science Center, Thousand Oaks, CA, 1990, pp. 495-507.

2. D.E. Albert and A.W. Thompson, "Creep Behavior of Ti-24 Al-11 Nb," in *Microstructure/Property Relationships in Titanium Aluminides and Alloys*, Y.-W. Kim and R.R. Boyer, eds., TMS-AIME, Warrendale, PA (1991) 399-406.

3. A.W. Thompson and T.M. Pollock, "Creep of $\alpha_2 + \beta$ Titanium Aluminide Alloys," *ISIJ Internat. Jnl.*, 31 (1991) 1138-1145.

4. D.E. Albert and A.W. Thompson, "Microstructural Effects in Creep of Ti-24 Al-11 Nb Polycrystals," *Metall. Trans. A*, 23A (1992) 3035-3043.

5. D. E. Albert and A.W. Thompson, "Mechanisms of Creep in Ti-24 Al-11 Nb," *Metall. Trans. A*, submitted.

6. A.W. Thompson, "Micromechanisms of Fracture in Titanium Aluminides," *Proc. 7th Int. Conf. on Titanium*, F.H. Froes, ed., TMS-AIME, Warrendale, PA, in press.

7. D. E. Albert and A.W. Thompson, "Microstructure and Creep of Ti-24 Al-11 Nb," *Proc. 7th Int. Conf. on Titanium*, F.H. Froes, ed., TMS-AIME, Warrendale, PA, in press.

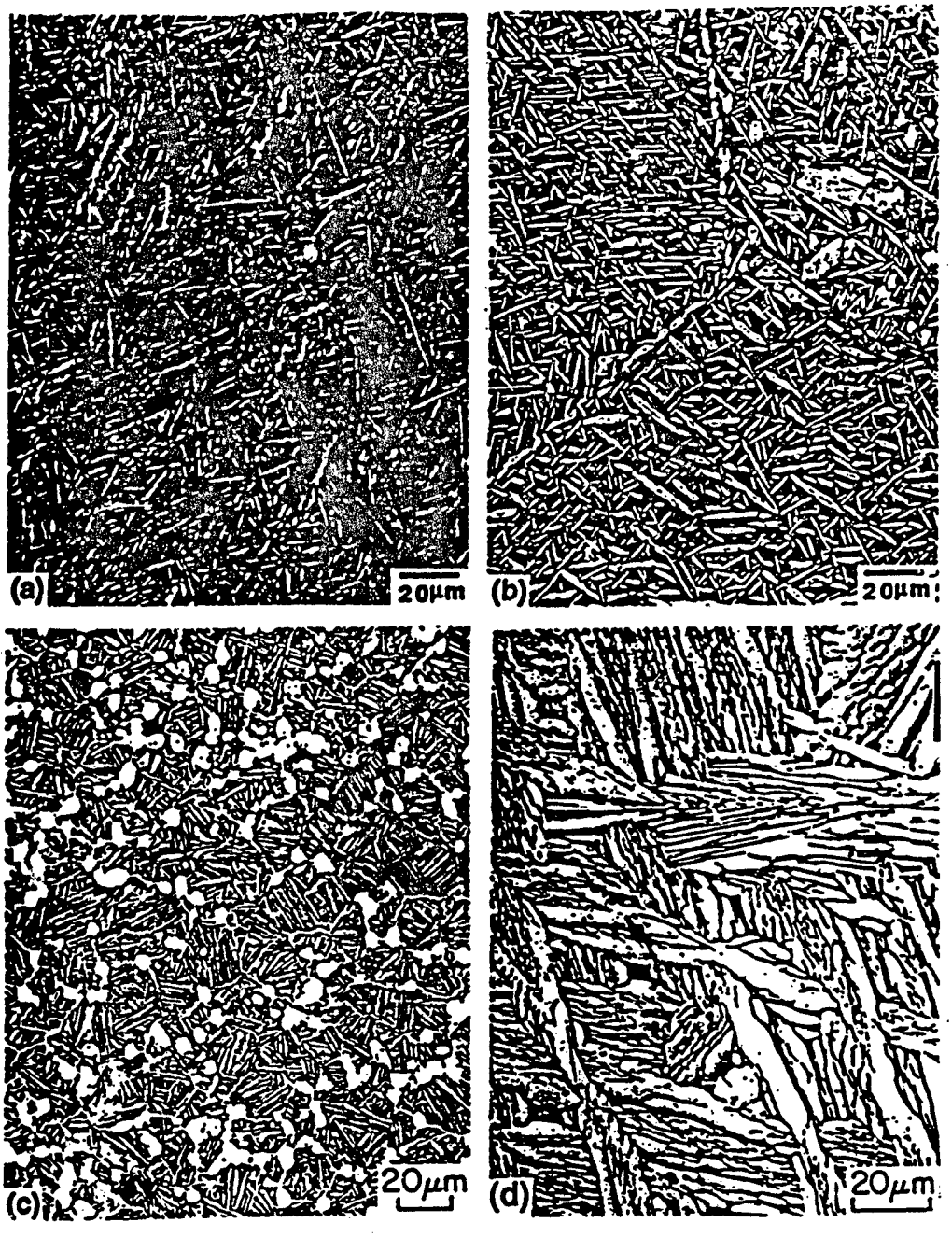

Fig. 1. Examples of microstructural range observed in $\alpha_2+\beta$ titanium aluminide alloys. (a) Widmanstätten or basketweave morphology of α_2 plates, formed in Ti-25-10-3-1 on cooling from the β phase at 0.5 K/s. (b) Coarser Widmanstätten α_2 plates, formed in Ti-25-10-3-1 on cooling from the $\alpha_2+\beta$ two-phase region at 0.5 K/s. (c) Primary α_2 and "packet" α_2 plates in Ti-25-10-3-1 cooled from the $\alpha_2+\beta$ two-phase region. (d) Colonies of α_2 plates in Ti-24-11 cooled from 1000°C (low in the $\alpha_2+\beta$ two-phase region) at 5 K/s.

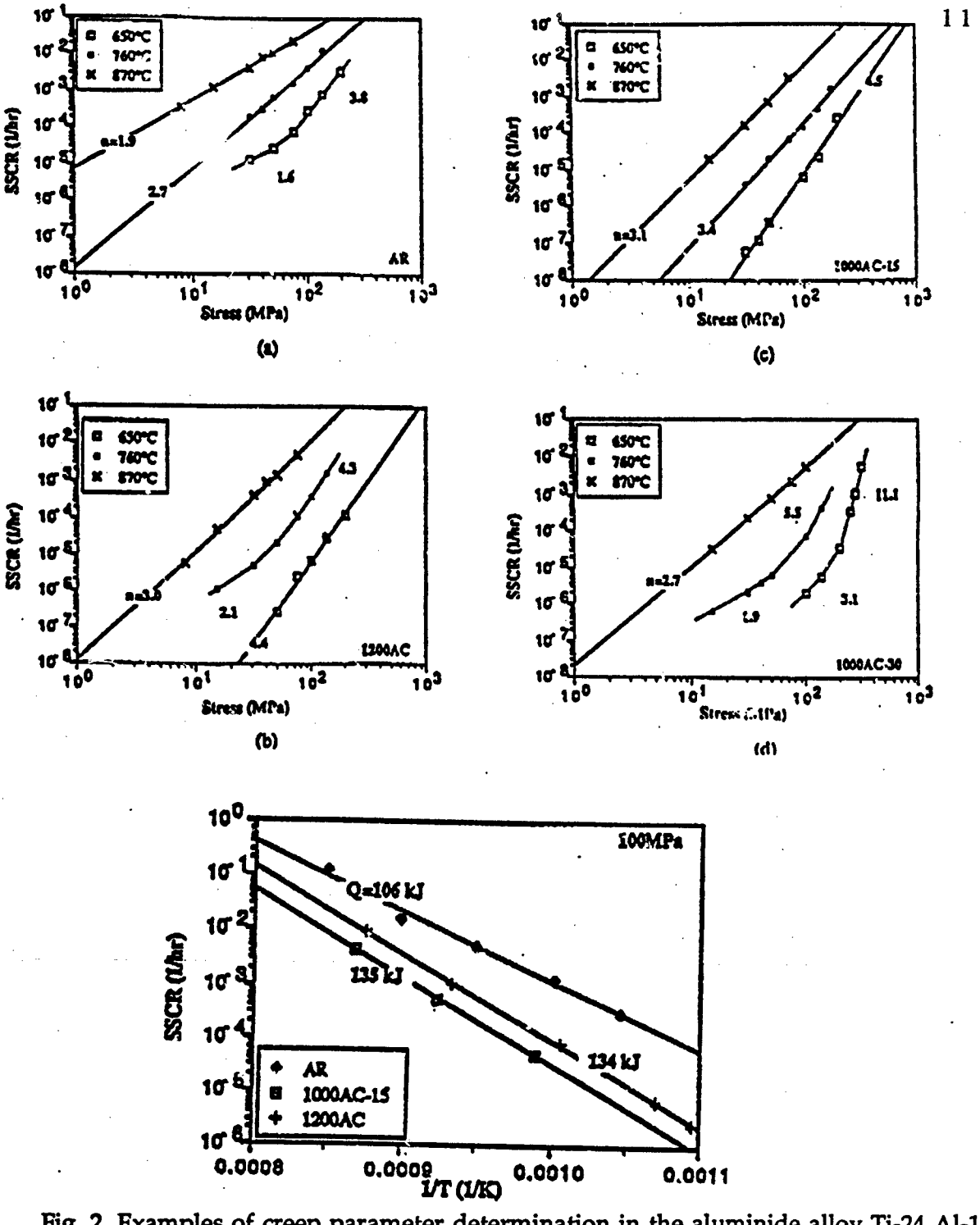

Fig. 2. Examples of creep parameter determination in the aluminide alloy Ti-24 Al-11 Nb. (a) to (d), top, stress exponent, n, determination for four different microstructures. Bottom, activation energy determination for 100 MPa applied stress, for three different microstructures. From refs. 4 and 5, p. 9.

Part 2

TERNARY ADDITIONS TO TiAl ALLOYS

James M. Howe, Principal Investigator

The second year of this program concentrated on understanding the atomic structure and deformation mechanisms of the α_2 and γ phases in TiAl base alloys, and the effects of ternary elements on these features. Addition of Ta to TiAl was found to change both the morphology and interfacial structure of α_2 precipitates in the γ matrix. Since these features have a large influence on the mechanical properties of TiAl-base alloys, the addition of elements such as Ta offers a possible means of manipulating the microstructure to optimize the mechanical properties. Several new mechanisms of room-temperature deformation which involve twinning of the γ phase were also analyzed by high-resolution transmission electron microscopy. These mechanisms have been shown elsewhere to be particularly important at high strains, and capable of providing considerable plasticity to the normally rather brittle γ phase. Examples of these observations, from ref. 3, below, are attached.

Several research papers which were started under a previous AFOSR grant were completed during this year, and a full list of publications is given below. A separate report on the concluding period of the subcontract to the University of Virginia, for calendar year 1991, has also been submitted to AFOSR and to Carnegie Mellon University, the primary contractor.

AFOSR-supported publications

1. S.R. Singh and J.M. Howe, "High-Resolution Electron Microscopy of Interfaces in TiAl Alloys," in *Proc. XIIth International Congress for Electron Microscopy*, San Francisco Press, San Francisco, CA (1990), p. 316.

2. J.Y. Huh, J.M. Howe and W.C. Johnson, "Analytical Electron Microscopy of Coherent and Incoherent $\alpha + \alpha_2$ Phase Equilibria in a Ti-16.64% Al Alloy," *Scripta Metall. Mater.*, 24 (1990) 2007.

3. S.R. Singh and J.M. Howe, "Effect of Ta on Twinning in TiAl," *Scripta Metall. Mater.*, 25 (1991) 485.

4. S.R. Singh and J.M. Howe, "Effect of Ta on the Structure and Dynamics of γ/α_2 Interfaces in TiAl," in *High Temperature Ordered Intermetallic Alloys IV*, MRS Symposium Vol. 213, L. Johnson, D.P. Pope and J.O Stiegler, eds., Mater. Res.

Soc., Pittsburgh (1991) 435.

5. T. Furuhara, J.M. Howe and H.I. Aaronson, "Interphase Boundary Structures of Intragranular Proeutectoid α Plates in a Hypoeutectoid Ti-Cr Alloy," *Acta Metall. Mater.*, 39 (1991) 2873.

6. S.R. Singh and J.M. Howe, "Studies on the Deformation Behavior of Interfaces in ($\gamma + \alpha_2$) Titanium Aluminide by High-Resolution Electron Microscopy," *Phil. Mag. Lett.*, in press.

7. S.R. Singh and J.M. Howe, "High-Resolution Electron Microscopy of γ/α_2 Interfaces in Titanium Aluminide," *Phil. Mag. A*, in press.

8. S.J. Rozeveld, J.M. Howe and S Schmauder, "Measurement of Residual Strains in an Al-SiC_w Composite Using Convergent-beam Electron Diffraction," *Acta Metall. Mater.*, in press.

9. S.J. Rozeveld and J.M. Howe, "Determination of Multiple Lattice Parameters from Convergent-beam Electron Diffraction Patterns," *Ultramicroscopy*, submitted.

10. S.R. Singh and J.M. Howe, "High-Resolution Transmission Electron Microscopy of Dislocation Reactions at Twin Intersections in γ TiAl," *Acta Metall. Mater.*, in preparation.

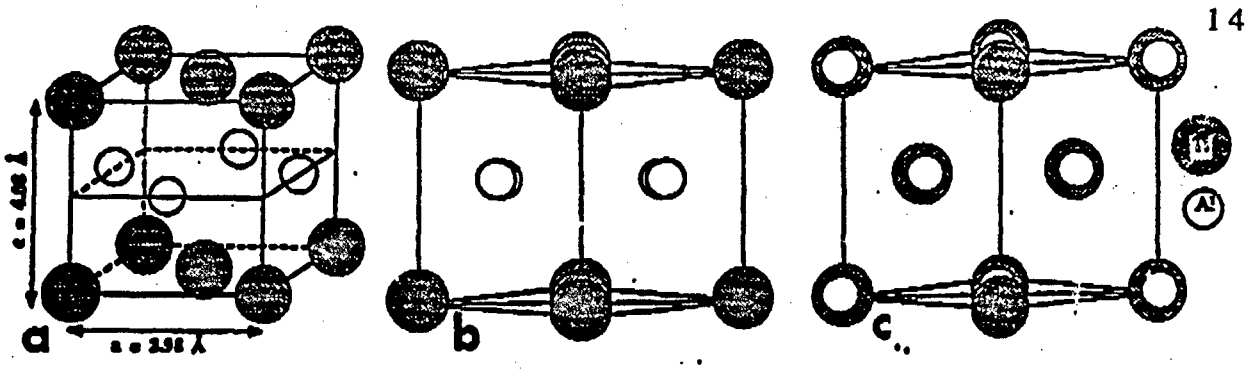

FIG. 1. (a) TiAl ($L1_0$) crystal structure with perspective views along (b) $[\bar{1}10]$ and (c) $[10\bar{1}]$.

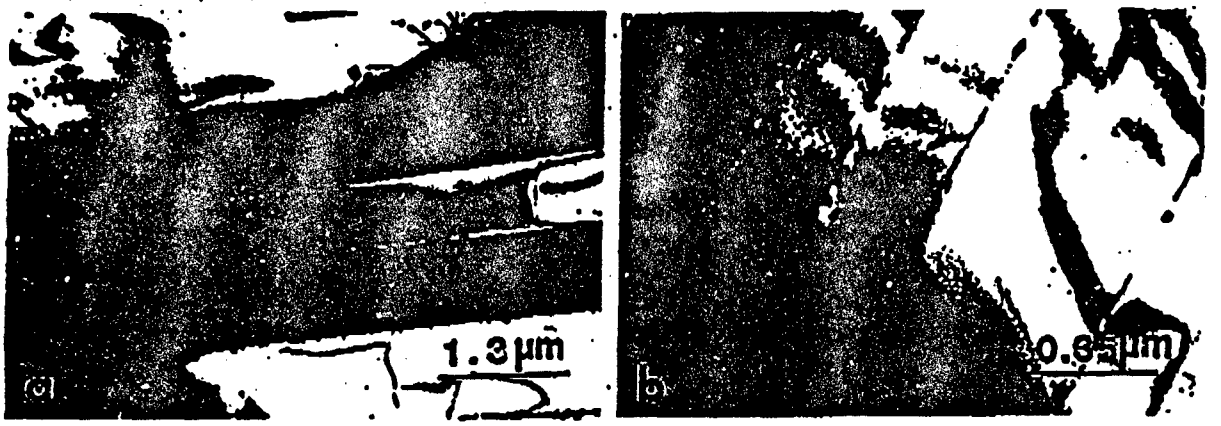

FIG. 2. Electron micrographs showing $[11\bar{2}](111)$ twins in (a) binary alloy and (b) ternary alloy.

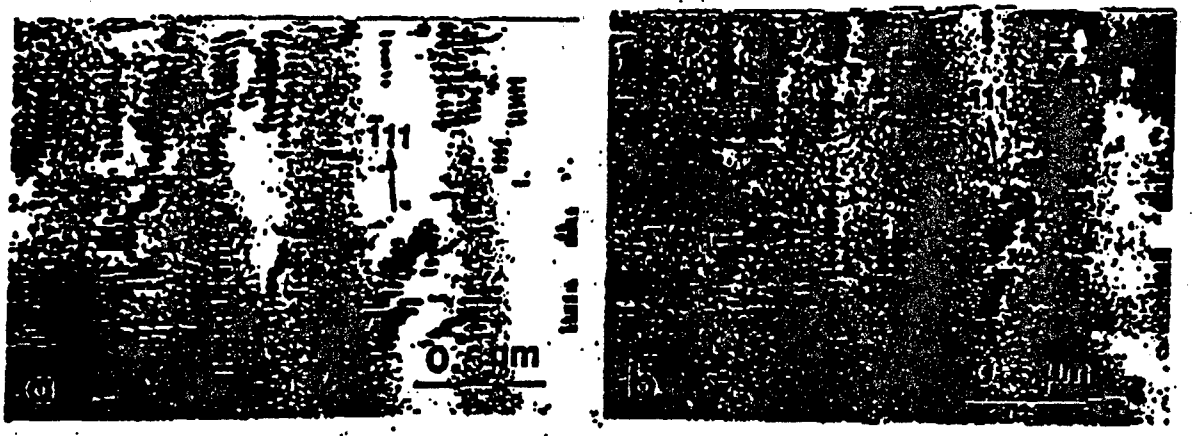

FIG. 3. Electron micrographs showing segmented stacking-faults in ternary alloy with operating reflection $g=\bar{1}11$ and $z=[211]$, (a) bright-field image and (b) dark-field image.

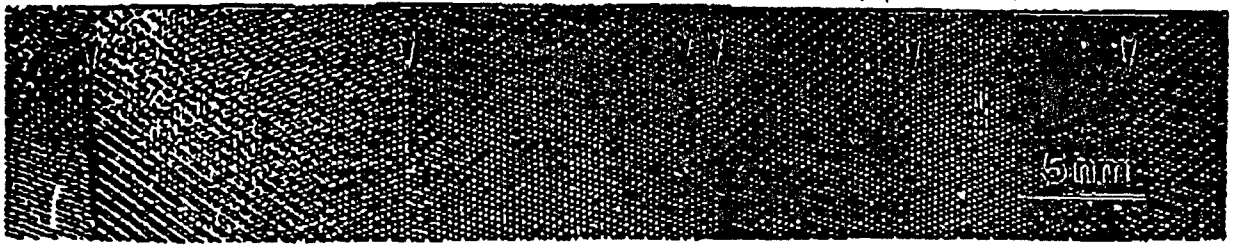

FIG. 4. HRTEM of twins in ternary alloy in $[\bar{1}10]$ orientation showing all the lamellae in the same orientation.